Environmental Impact: Concept, Consequences, Measurement☆

EW Chu, Port Townsend, WA, United States
JR Karr, University of Washington, Seattle, WA, United States

Glossary

Biological integrity Wholeness of a living system, including the capacity to sustain the full range of organisms and processes having evolved in a region.
Biosphere The totality of life on Earth, the parts of the world where life exists.
Biota Living organisms.
Biotic impoverishment Systematic reduction in Earth's capacity to support life.
Ecosystem engineers Organisms that shape their environment, including organisms that create or modify the environments of other organisms.
Environment Surroundings; the complex of physical, chemical, and biotic factors acting upon a living system and influencing its form, function, and survival; the biophysical realities that govern everything on Earth.
Health A flourishing condition, well-being; capacity for self-renewal.
Impact A forceful contact; a major effect of one thing on another.

One Species' Impact

All organisms change their environment as they live, grow, and reproduce. Over millennia, organisms evolve to contend with changes in their environment. Those that do not adapt go extinct. Those that survive are molded by natural selection as the environment changes. Even unusual or seemingly catastrophic events, like volcanic eruptions, are an integral part of the ecological contexts to which organisms adapt over long time spans.

Some organisms, like beavers and elephants, change their surroundings so much that they have been called ecosystem engineers. Beaver dams alter the flow of rivers, increase dissolved oxygen in downstream waters, create wetlands, and modify streamside zones. African elephants convert wooded savanna to open grassland by toppling trees as they browse. In evolutionary terms, changes like these brought about by living things, including ecosystem engineers, have been slow and incremental. Ecosystem engineers and their effects have long been part of evolving ecological systems.

People, in contrast, have become ecosystem engineers on a whole new scale in time and space. Human effects since the Industrial Revolution – including many that may be invisible to a casual observer – are recent and outside the evolutionary experience of most organisms. Moreover, such effects unfold faster and on a scale far greater than any effects of past ecosystem engineers. As a result, over the past two centuries – barely more than two human lifetimes – humans have disrupted living and nonliving systems everywhere. Understanding the nature and consequences of humans' environmental impacts – and managing these impacts to protect the well-being of human society and other life on Earth – is humanity's greatest challenge.

Human Environmental Impact Through Time

The human evolutionary line began in Africa about 7 million years ago (Ma). It took some 5 or 6 million years (My) for protohumans to spread from Africa to Asia and then to Europe. These early humans, like other primates, made their living by seeking food and shelter from their environment, gathering plant foods, and hunting easy-to-kill prey. Sometimes they also experienced threats *from* their environment, including accidents, droughts, vector-borne diseases, and attacks from predators. At this stage, with relatively low population densities and limited technologies, humans were not ecosystem engineers.

By some 50,000 years ago, however, humans had learned to use fire and to cook their food; they had developed complex tools, weapons, and language and created art. On local scales, these modern humans were very much ecosystem engineers. Sometimes their enhanced abilities to make a living outstripped their local environment's capacity to provide that living, and they disrupted local ecological systems. On several continents, for example, humans hunted large mammals to the point where many, such as the marsupial lion of Australia, went extinct. As humans became more efficient at exploiting their local environments, they spread

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farther. By 13,000 years ago, modern humans had spread to all continents and many islands across the globe. Then, about 10,000 years ago, people began to domesticate plants and animals. Instead of searching for food, they began to produce food.

Food production changed the course of human and environmental history. Domestication of plants and animals enabled people to adopt a sedentary lifestyle. As detailed by geographer and ecologist Diamond (1997, 2002), populations grew as agriculture developed, because larger sedentary populations both demanded and enabled more food production. Local ecological disruptions became more numerous and widespread and more intense. With animal domestication, contagious diseases of pets and livestock adapted to new, human hosts. Diseases spread more quickly in crowded conditions; inadequate sanitation compounded the effects. From agriculture, civilization followed and, with it, cities, writing, advanced technology, and political empires. In just 10,000 years, these developments led to some 7.5 billion people on Earth, industrial societies, and a global economy founded on complicated technologies and fossil fuels. Humans have emerged as ecosystem engineers on a global scale. The ecological disruptions we cause are no longer just local or regional but global, and we have become the principal threat *to* the environment.

Yet despite today's advanced technologies, people depend as much on their environments as other organisms do. History, not just ecology, has been very clear on this point. From the Old Kingdom of Egypt more than 4000 years ago to the culture that created the huge stone monoliths on Easter Island between AD 1000 and 1550 to the 1930s Dust Bowl on the Great Plains of North America, civilizations or ways of life have prospered and failed by using and (mostly unwittingly) abusing natural resources.

In Old Kingdom Egypt, the resource was the valley of the Nile, richly fertilized with sediment at each river flooding, laced with canals and side streams, blessed with a luxuriant delta. Agriculture flourished and populations swelled, until unusually severe droughts brought on the civilization's collapse. On Easter Island, the resource was trees, which gave Polynesians colonizing the island the means to build shelter, canoes for fishing the open waters around the island, and log rollers for moving the ceremonial stone monuments the island is famous for. Deforestation not only eliminated the people's source of wood, but also further deprived the already poor soil of nutrients and made it impossible to sustain the agriculture that had sustained the island's civilization. On the dry Great Plains of North America, settlers were convinced that rain would follow the plow, and so they plowed homestead after homestead, only to watch their homesteads' soils literally blow away in the wind.

In these cases and many others, human civilizations damaged their environments, and their actions also worsened the effects on their civilizations of climatic or other natural cycles. In each case, short-term success compromised a culture's long-term stability: The culture of Old Kingdom Egypt enabled its people to prosper on the Nile's natural bounty, but prolonged, unprecedented drought brought starvation and political disorder. Easter Islanders thrived and populated the island until its resources were exhausted. Dust Bowl farmers lived out their culture's view of dominating and exploiting land to the fullest. The inevitable outcome in all three cases was a catastrophe for the immediate environment and the people it supported – not only because the people were unprepared to cope with dramatic natural changes in their environments but because their own actions magnified the disastrous effects of those changes.

In the 21st century, humans are ecosystem engineers on a planetwide scale, threatening the life-sustaining capacity of all of Earth's environmental "spheres":

- *Geosphere (lithosphere): Earth's crust and upper mantle, containing nonrenewable fossil fuels, minerals, and nutrients that plants require*. The activities of plants, animals, and microorganisms weather mineral soils and rocks, create organic soils, and alter erosion and sedimentation rates. People mine minerals, metals, and gems; extract fossil fuels including coal, oil, and natural gas; and increase erosion and sedimentation by removing or altering natural plant cover through agriculture, logging, and urbanization.
- *Atmosphere: the thin envelope of gases encircling the planet*. Living systems modify the atmosphere, its temperature, and the amount of water it contains by continually generating oxygen and consuming carbon dioxide through photosynthesis and by affecting the amount and forms of other gases. People release toxic chemicals into the air and alter the climate by raising the atmospheric concentration of greenhouse gases, such as carbon dioxide and methane, through industrialized agriculture; deforestation; and the burning of fossil fuels in motor vehicles, ships, trains, planes, and power plants.
- *Hydrosphere: Earth's atmospheric water vapor; its liquid surface and underground water; its mountain snow and glaciers; and its polar ice caps, oceanic icebergs, and terrestrial permafrost*. Living systems alter the water cycle by modifying the Earth's temperature and the amount of water plants send into the atmosphere through a process called evapotranspiration. People build dams, irrigation canals, drinking-water delivery systems, and wastewater treatment plants. They use water to generate electricity; they mine groundwater from dwindling underground aquifers for farming as well as drinking; they alter the flows of surface waters for everything from transportation to flood control; they drain wetlands to gain land area and abate waterborne diseases; they even inject vast quantities of water underground to extract natural gas, contaminating groundwater and triggering earthquakes. Moreover, modern humans' effects on global climate are disrupting the entire planetary water cycle.
- *Biosphere: the totality of life on Earth, the parts of the world where life exists*. Life emerged on Earth 3.9 billion years ago and has sustained itself through changes in form, diversity, and detail since then. No planet yet discovered supports complex life as we know it on Earth. As predators, people have decimated or eliminated wild animal populations worldwide. As domesticators of animals and plants, people have massively reshaped landscapes by cutting forests, burning and plowing grasslands, building cities, desertifying vast areas, and overharvesting fish and shellfish. Human actions have precipitated a spasm of extinctions that today rivals five previous mass extinctions set off by astronomical or geological forces, each of which eliminated more than 70% of species then existing.

People themselves may be thought of as a sphere within the greater biosphere: the *ethnosphere*, or the sum total of all thoughts and intuitions, myths and beliefs, ideas and inspirations brought into being by the human imagination since the dawn of consciousness. Observes anthropologist Davis (2009, p. 2), who coined and defined the term in 2002, just as the greater biosphere is being severely eroded, so too is the ethnosphere, and at a much faster pace.

Today, the scientific consensus is that, for the first time in Earth's history, one species – *Homo sapiens* – rivals astronomical and geological forces in its impact on life on Earth. Welcome to the Anthropocene.

Biotic Impoverishment

The first step in dealing with the present impact of human activity is to correctly identify the nature of humanity's relationship with the environment and how human actions affect that relationship. Many people still see the environment as something people must overcome, or they regard environmental needs as something that ought to be balanced against human needs (eg, jobs vs. the environment). Most people still regard the environment as a provider of commodities or a receptacle for waste.

When asked to name humanity's primary environmental problems, people typically think of running out of nonrenewable raw materials and energy or about water and air pollution. Environmental research and development institutions focus on ways technology can help solve each problem, such as fuel cells to supply clean, potentially renewable energy or scrubbers to curb smokestack pollution. Even when people worry about biodiversity loss, they are concerned primarily with stopping the extinction of species, rather than with understanding the underlying losses leading up to species extinctions or the broader biological crisis that extinctions signal.

These perspectives miss a crucial point: the reason pollution, energy use, extinction, and dozens of other human impacts matter is their impact on life. Ecosystems, particularly their living components, have always provided the capital to fuel human economies. When populations were small, humans making a living from nature's wealth caused no more disruption than other species. But with upward of 7.5 billion people occupying or using resources from every place on Earth, humans are overwhelming the ability of other life-forms to make a living and depleting the planet's natural wealth. One species is compromising Earth's ability to support the living systems that evolved on the planet over millions of years. The systematic reduction in Earth's capacity to support life – which Woodwell (1990) termed biotic impoverishment – is thus the most important human-caused environmental impact. At best, the ethics of this impact are questionable; at worst, it is jeopardizing our own survival.

The connection between biotic impoverishment and extinction is intuitively obvious. By overharvesting fish, overcutting forests, overgrazing grasslands, or paving over land for cities, we are clearly killing other organisms outright or eliminating their habitats, thereby driving species to extinction and impoverishing the diversity of life. But biotic impoverishment takes many forms besides extinction. It encompasses three categories of human impacts on the biosphere: (1) indirect depletion of living systems through alterations in physical and chemical environments, (2) direct depletion of nonhuman life, and (3) direct degradation of human life (**Table 1**; Karr and Chu, 1995). Identifying and understanding the biological significance of our actions – their effects on living systems, including our own social and economic systems – are the keys to developing effective ways to manage our impacts.

Indirect Biotic Depletion

People affect virtually all the physical and chemical systems life depends on: water, soils, air, and the biogeochemical cycles linking them. Some human-driven physical and chemical changes have no repercussions on the biota; others do, becoming agents of biotic impoverishment.

Degradation of water

People probably spend more energy, money, and time trying to control the movement and availability of water than to manage any other natural resource. In the process, we contaminate water, move water across and out of natural basins, deplete surface and groundwater; modify the timing and amount of flow in rivers, straighten or build dikes to constrain rivers, and alter natural flood patterns. We change the amount, timing, and chemistry of fresh water reaching coastal regions, and we dry up wetlands, lakes, and inland seas. Our demands are outrunning supplies of this nonrenewable resource, and the scale of our transformations risks altering the planetary water cycle.

Physical alterations of the Earth's waters, combined with massive industrial, agricultural, and residential pollution, have taken a heavy toll on aquatic life. By 2015 almost one-fifth of the world's coral reefs had been destroyed, more than a third were under threat, and less than half were relatively healthy. Globally, the number of oceanic dead zones, where little or no dissolved oxygen exists, tripled during the last 30 years of the 20th century. The biota of freshwater systems has fared no better. A 4-year survey of the freshwater fishes inhabiting Malaysian rivers in the late 1980s found only 46% of 266 known Malaysian species. Some 40% of North America's freshwater fishes are at risk of extinction; two-thirds of freshwater mussels and crayfishes and one-third of amphibians that depend on aquatic habitats in the United States are rare or imperiled.

Humans use at least 54% of the Earth's accessible water runoff, a figure that is likely to grow to 70% by 2025. By then, more than a third of the world's population could suffer shortages of fresh water for drinking and irrigation. Groundwater aquifers in many of the world's most important crop-producing regions are being drained faster than they can be replenished: a study published in 2010 found that the rate of groundwater depletion worldwide had more than doubled from 1960 to 2000. Natural

Table 1 The many faces of biotic impoverishment[a]

Indirect depletion of living systems through alterations in physical and chemical environments

1. Degradation of water (redirected flows, depletion of surface and groundwater, wetland drainage, organic enrichment, destruction and alteration of aquatic biota)
2. Soil depletion (destruction of soil structure, erosion, salinization, desertification, acidification, nutrient leaching, destruction and alteration of soil biota)
3. Chemical contamination (land, air, and water pollution from pesticides, herbicides, heavy metals, and toxic synthetic chemicals; atmospheric ozone depletion; ocean acidification; fish kills; extinctions; biotic homogenization and biodiversity loss; bioaccumulation; hormone disruption; immunological deficiencies; reproductive and developmental anomalies; respiratory diseases; intergenerational effects)
4. Altered biogeochemical cycles (alteration of the water cycle; nutrient enrichment; acid rain; fossil fuel combustion; particulate pollution; degradation of land and water biota; outbreaks of pests, pathogens, and red tides)
5. Global climate change (rising greenhouse gas concentrations, altered precipitation and airflow patterns, rising temperatures, effects on individual and community health, shifts among and within global ecosystems)

Direct depletion of nonhuman life

1. Overharvest of renewable resources such as fish and timber (depleted populations, extinctions, altered food webs)
2. Habitat fragmentation and destruction (extinctions, biotic homogenization, emerging and reemerging pests and pathogens, loss of landscape mosaics and connectivity)
3. Biotic homogenization (extinctions and invasions, lost biodiversity among food crops and livestock)
4. Genetic engineering (homogenization of crops, antibiotic resistance, potential extinctions and invasions if genes escape, other unknown ecological effects)

Direct degradation of human life

1. Emerging and reemerging diseases (occupational hazards, asthma and other respiratory ills, pandemics, Ebola, AIDS, hantavirus, tuberculosis, Lyme disease, West Nile fever, chikungunya, Zika virus disease, antibiotic resistance, diseases of overconsumption and stress, altered human microbiomes)
2. Loss of cultural diversity (religious wars and genocide, loss of cultural and linguistic diversity, loss of knowledge)
3. Reduced quality of life (malnutrition and starvation, failure to thrive, poverty)
4. Environmental injustice (environmental discrimination and racism; economic exploitation; growing gaps between rich and poor individuals, segments of society, and nations; environmental refugees; gender inequities; trampling of the environmental and economic rights of future generations)
5. Political instability (civil violence, especially under intransigent regimes; resource wars; international terrorism; increased number of refugees)
6. Cumulative effects (environmental surprises, increased frequency of catastrophic natural events, boom-and-bust cycles, interactions between disease and biodiversity, collapse of civilizations because of environmental degradation)

[a]Modified from Karr, J.R., Chu, E.W., 1995. Ecological integrity: Reclaiming lost connections. In: Westra, L., Lemons, J. (Eds.), Perspectives in Ecological Integrity, pp. 34–48. Dordrecht: Kluwer Academic.

flood regimes, as in the Nile River basin, no longer spread nutrient-rich silt across floodplains to nourish agriculture. Indeed, the High Dam at Aswan traps so much silt behind it that the Nile delta, essential to Egypt's present-day economy, is sinking into the Mediterranean. Whole inland seas, such as the Aral Sea in Uzbekistan, are drying up because the streams feeding them contain so little water. In addition to eliminating habitat for resident organisms, the sea's drying is bringing diseases to surrounding human populations. Indeed, diseases caused by waterborne pathogens are making a comeback even in industrialized nations.

In the past five or six decades, the number of large dams on the world's rivers grew more than seven times, to more than 40,000 today. The mammoth Three Gorges Dam across China's Yangtze River, completed in 2006, created a 660-km-long serpentine lake behind it. The dam displaced more than 1 million people and may force the relocation of another 4 million from the reservoir region, which, at 58,000 km^2, is larger than Switzerland. The dam has greatly altered ecosystems on the Yangtze's middle reaches, compounding perils already faced by prized and endemic fishes and aquatic mammals. The sheer weight of the water and silt behind the concrete dam raises the risk of landslides and strains the region's geological structure, while water released from the dam eats away at downstream banks and scours the bottom. And by slowing the flow of the Yangtze and nearby tributaries, the dam blocks the river's ability to flush out and detoxify pollutants from upstream industries.

Soil depletion

Hardly just dirt, soil is a living system that makes it possible for raw elements from air, water, and bedrock to be physically and chemically assembled, disassembled, and reassembled with the aid of living macro- and microorganisms into life above ground. Accumulated over thousands of years, soil cannot be renewed in any time frame useful to humans alive today, or even to their great-grandchildren.

Humans degrade soils when they compact it, erode it, disrupt its organic and inorganic structure, raise its salinity, and cause desertification. Urbanization, logging, mining, overgrazing, alterations in soil moisture, air pollution, fires, chemical pollution, and leaching out of minerals all damage or destroy soils. Thanks to removal of vegetative cover, mining, agriculture, and other activities, the world's topsoils are eroded by wind and water ten to hundreds of times faster than they are renewed (at roughly 10 t ha^{-1} $year^{-1}$).

Soils constitute the foundation of human agriculture, yet agriculture, including livestock raising, is the worst culprit in degrading soils. Agricultural practices have eroded or degraded more than 40% of present cropland. Over the last half century, some 24,000 villages in northern and western China have been overrun by the drifting sands of desertification. Besides topsoil erosion, the damage includes salting and saturation of poorly managed irrigated lands; compaction by heavy machinery and the hooves of livestock; and pollution from excessive fertilizers, animal wastes, and pesticides.

Living, dead, and decomposing organic matter is the key to soil structure and fertility. Soil depleted of organic matter is less permeable to water and air and thus less able to support either aboveground plants or soil organisms. The linkages between soil's inorganic components and the soil biota – naturalist Wilson's (1987) "little things that run the world" – are what give soil its life-sustaining capacity. Echoing Wilson, Montgomery and Biklé (2016, p. 88) make it abundantly clear in *The Hidden Half of Nature* that "soil fertility springs from biology – all of the interactions between fungi, plants, and other soil organisms," most of them invisible. Clear-cut logging, for example, which destroys the soil biota – especially the close associations among fungi and plant roots – unleashes a whole series of impoverishing biotic effects both below and above ground.

Chemical contamination

In 1962, Rachel Carson's landmark book *Silent Spring* alerted the world to the pervasiveness of synthetic chemicals produced since World War II. As many as 100,000 synthetic chemicals are in use today. True to one company's slogan, many of these have brought "better living through chemistry," providing new fabrics and lighter manufacturing materials, antibiotics, and life-saving drugs.

But industrial nations have carelessly pumped chemicals into every medium. Chemicals – as varied as pesticides, heavy metals, prescription drugs flowing out of sewage plants, and cancer-causing by-products of countless manufacturing processes – now lace the world's water, soil, and air and the bodies of all living things, including people. Chemicals directly poison organisms; they accumulate in physical surroundings and are passed through and, in many cases, concentrated within portions of the food web. Chemicals cause cancer, interfere with hormonal systems, provoke asthma, and impair the functioning of immune systems. They have intergenerational effects, such as intellectual impairment in children whose mothers have eaten contaminated fish. What's more, over half a century of pesticide and antibiotic overuse has bred resistance to these chemicals among insects, plants, and microbes, giving rise to new and reemerging illnesses.

Many chemicals travel oceanic and atmospheric currents to sites far from their source. Sulfur emissions from the US Midwest, for example, fall to earth again as acid rain in Europe, killing forests and so acidifying streams and lakes that they, too, effectively die. China's burning of soft coal sends air pollution all the way to northwestern North America; the heavy haze hanging over China's chief farming regions may be cutting agricultural production by a third. Chlorofluorocarbons (CFCs), once widely used as refrigerants, have damaged the atmospheric ozone layer, which moderates how much ultraviolet radiation reaches the Earth, and opened ozone holes over the Arctic and Antarctic.

Even more alarming is an unprecedented acidification of the oceans that has only recently attracted the attention of major scientific research consortiums. Acid added to the world ocean by human activity has lowered the ocean's pH; it is lower now than it has been in 20 My, which translates into a 30% increase in sea-surface acidity since industrialization began. The future of marine life looks bleak in an ocean acidifying at this speed and intensity. As the concentration of hydrogen ions rises, calcium carbonate begins to dissolve out of the shells or skeletons of organisms such as tropical corals, microscopic foraminifera, and mollusks. Further, as hydrogen ions combine with the calcium carbonate building blocks the organisms need, it becomes harder for them to extract this compound from the water and build shells in the first place.

Although many of the most obviously deadly chemicals were banned in the 1970s, they continue to impoverish the biota. Polychlorinated biphenyls – stable, nonflammable compounds once used in electrical transformers and many other industrial and household applications – remain in the environment for long periods, cycling among air, water, and soils and persisting in the food web. They are found, far from their sources, in polar bears and arctic villagers; they are implicated in reproductive disorders, particularly in such animals as marine mammals, whose long lives, thick fat layers where chemicals concentrate, and position as top predators make them especially vulnerable.

The agricultural pesticide DDT, sprayed with abandon in the 1940s and 1950s, even directly on children, had severely thinned wild birds' eggshells by the time it was banned in the United States. Populations of birds such as the brown pelican and bald eagle had dropped precipitously by the 1970s, although they have recovered enough for the species to be taken off the US endangered species list (the bald eagle in 2007 and the brown pelican in 2009). Reproduction of central California populations of the California condor, in contrast, continues to be threatened by DDT breakdown products, which, decades after the pesticide was banned, are still found in the sea lion carcasses the birds sometimes feed on.

Carson's book revealed the real danger of chemical pollutants: they have not simply perturbed the chemistry of water, soil, and air but harmed the biota as well. The list of chemicals' effects on living things is so long that chemical pollution equals humans' environmental impact in most people's minds, but it is only one form of biotic impoverishment.

Altered biogeochemical cycles

All the substances found in living things – such as water, carbon, nitrogen, phosphorus, and sulfur – cycle through ecosystems in biogeochemical cycles. Human activities modify or have the potential to modify all these cycles. Sometimes the results stem from changing the amount or the precise chemistry of the cycled substance; in other cases, humans change biogeochemical cycles by changing the biota itself.

Freshwater use, dams, and other engineering ventures affect the amount and rate of river flow to the oceans and increase evaporation rates, directly affecting the water cycle and indirectly impoverishing aquatic life. Direct human modifications of living systems also alter the water cycle. In South Africa, European settlers supplemented the treeless native scrub, or fynbos, with trees like pines and Australian acacias from similar Mediterranean climates. But because these trees are larger and thirstier than the native scrub, regional water tables have fallen sharply.

Human activity has disrupted the global nitrogen cycle by greatly increasing the amount of nitrogen fixed from the atmosphere (combined into compounds usable by living things). The increase comes mostly from deliberate addition of nitrogen to soils as fertilizer but also as a by-product of the burning of fossil fuels. Agriculture, livestock raising, and residential yard maintenance chronically add tons of excess nutrients, including nitrogen and phosphorus, to soils and water.

The additions are often invisible; their biological impacts are often dramatic. Increased nutrients in coastal waters, for example, trigger blooms of toxic dinoflagellates – the algae that cause red tides, fish kills, and tumors and other diseases in varied sea creatures. When huge blooms of algae die, they fall to the seafloor, where their decomposition robs the water of oxygen so that fishes and other marine organisms can no longer live there. With nitrogen concentrations in the Mississippi River two to three times as high as they were 50-plus years ago, a gigantic dead zone forms in the Gulf of Mexico every summer. In summer 2010 this dead zone covered 20,000 km^2, and every year thereafter it has been more than twice the target size set by the scientists who have studied this phenomenon for the past 30 years.

The burning of fossil fuels is transforming the carbon cycle, primarily by raising the atmospheric concentration of carbon dioxide. With other greenhouse gases, such as methane and oxides of nitrogen, carbon dioxide helps keep Earth's surface at a livable temperature and drives plant photosynthesis. But since the Industrial Revolution, atmospheric carbon dioxide concentrations have risen nearly 40% and are now disrupting the planet's climate. In addition, the effects of catastrophic oil spills like the one that followed the April 2010 explosion of the Deepwater Horizon drilling rig in the Gulf of Mexico – and the effects of the chemicals used to disperse the resulting plumes of oil – have reverberated for decades.

Global climate change

In its 2014 report, written and reviewed by more than 3800 scientists from the world's 195 countries, the typically cautious Intergovernmental Panel on Climate Change (IPCC) (2014) stated, "Warming of the climate system is unequivocal." Reflecting worldwide scientific consensus, the report says, "Human influence on the climate system is clear," and recent human-caused "emissions of greenhouse gases are the highest in history" (p. 2). "The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen." Atmospheric concentrations of greenhouse gases are the highest they have been "in at least the last 800,000 years," and their effects are "extremely likely to have been the dominant cause of observed global warming" (p. 4). The 20th century in the Northern Hemisphere was the warmest of the past millennium. All but 1 of the first 15 years of the 21st century were globally the warmest in history, and 2015 was the hottest year ever recorded.

Higher concentrations of greenhouse gases, including carbon dioxide, and higher global temperatures set in motion a whole series of effects. Where other nutrients are not limiting, rising carbon dioxide concentrations may enhance plant photosynthesis and growth. With higher temperatures, spring arrives one or more weeks earlier in the Northern Hemisphere. Rising temperatures are shifting the ranges of many plants and animals – both wild and domestic – potentially rearranging the composition and distribution of the world's biomes, as well as those of agricultural systems. The resulting displacements will have far-reaching implications not only for the displaced plants and animals but also for the goods and services people depend on from these living systems.

In addition, as shown in a study by Gleckler *et al.* (2016), the amount of heat energy absorbed by the oceans since 1865 – a total of about 300 ZJ, or 300×10^{21} J – doubled in just the 18 years from 1997 to 2015. Moreover, polar glaciers and ice sheets are receding. The Arctic has been warming twice as fast as the rest of the planet, and arctic sea ice melted at a near-record pace in 2010. With the sun heating newly open waters, winter refreezing takes longer, and the resulting thinner ice melts more easily the following summer. Rising global sea levels already threaten low-lying island nations. Large-scale circulation of global air masses is also changing and, with it, large-scale cycles in ocean currents, including the periodic warming and cooling in the tropical Pacific Ocean known as El Niño and La Niña, respectively.

All these shifts are affecting the distribution, timing, and amount of rain and snow, making the weather seem more unpredictable than ever. Unusually warm or cold winters, massive hurricanes like those that devastated the US Gulf Coast in 2005, severe droughts and flooding, and weather-related damage to human life and property are all predicted to increase with global climate change. In fact, according to a 2015 report from the Centre for Research on the Epidemiology of Disasters (affiliated with the World Health Organization), the frequency of climate-related events from 2000 to 2014 increased by 44% in comparison with the two decades from 1994 through 2013, even while the frequency of geophysical disasters remained broadly constant. Worldwide damage due to natural disasters from 1994 through 2013 – of which more than two-thirds stemmed from floods, storms, and other climate-related events – totaled at least $2.6 trillion.

Direct Depletion of Nonhuman Life

From their beginnings as hunter-gatherers, humans have become highly efficient, machine-aided ecosystem engineers and predators. We transform the land so it produces what we need or want; we harvest the oceans in addition to reaping our own fields; we cover the land, even agricultural land, with sprawling cities. All these activities directly affect the ability of other life-forms to survive and reproduce. We deplete nonhuman life by eliminating some forms and favoring others; the result is a loss of genetic, population, species, and higher-order taxonomic diversity.

We are irreversibly homogenizing life on Earth, in effect exercising an unnatural selection that is erasing the diversity generated by millions of years of evolution by natural selection. One species is now determining which other species will survive, reproduce, and thereby contribute the raw material for future evolution.

Overharvest of renewable resources

In the 1930s, so many sardines were harvested from the waters off Monterey's Cannery Row in California that the population collapsed, taking other sea creatures and people's livelihoods with it. After rebounding somewhat in the first decade of the 2000s, the species has still not recovered fully. According to the US National Marine Fisheries Service, nearly 80% of commercially valuable fishes of known status were overfished or fished to their full potential by 1993. Atlantic commercial fish species at their lowest levels in history include tuna, marlin, cod, and swordfish. Overfishing not only depletes target species but restructures entire marine food webs.

Marine mammals, including whales, seals, sea lions, manatees, and sea otters, were so badly depleted by human hunters that one species, Steller's sea cow, went extinct; many other species almost disappeared. In the 19th century, Russian fur traders wiped out sea otters along the central California coast. With the otters gone, their principal prey, purple sea urchins, overran the offshore forests of giant kelp, decimating the kelp fronds and the habitat they provided for countless other marine creatures, including commercially harvested fishes. Thanks to five decades of protection, marine mammal populations were slowly recovering – only to face food shortages as regional marine food webs unravel because of fishing, changing oceanic conditions, and contamination.

Timber harvest has stripped land of vegetation, from the Amazonian rainforest to mountainsides on all continents, diminishing and fragmenting habitat for innumerable forest and stream organisms, eroding soils, worsening floods, and contributing significantly to global carbon dioxide emissions. In the Northern Hemisphere, 10% or less remains of old-growth temperate rainforests. The uniform stands of trees usually replanted after logging do not replace the diversity lost with native forest, any more than monocultures of corn replace the diversity within native tallgrass prairies.

Habitat fragmentation and destruction

A great deal of human ecosystem engineering not only alters or damages the habitats of other living things but also often destroys those habitats. Satellite-mounted remote-sensing instruments have revealed transformations of terrestrial landscapes on a scale unimaginable in centuries past. Together, cropland and pastures occupy 40% of Earth's land surface. Estimates of the share of land wholly transformed or degraded by humans hover around 50%. Our roads, farms, cities, feedlots, and ranches either fragment or destroy the habitats of most large carnivorous mammals. Mining and oil drilling damage soil, remove vegetation, and pollute freshwater and marine areas. Grazing compacts soil and sends silt and manure into streams, where they harm stream life.

Landscapes that have not been entirely converted to human use have been cut into fragments. In *Song of the Dodo*, writer Quammen (1996) likens our actions to starting with a fine Persian carpet and then slicing it neatly into 36 equal pieces; even if we had the same square footage, we would not have 36 nice Persian rugs – only ragged, nonfunctional fragments. And in fact, we do not even have the original square footage because we have destroyed an enormous fraction of it.

Such habitat destruction is not limited to terrestrial environments. Human channelization of rivers may remove whole segments of riverbed. In the Kissimmee River of the US state of Florida, for example, channelization in the 1960s transformed 165 km of free-flowing river into 90 km of canal, effectively removing 35 km of river channel and drastically altering the orphaned river meanders left behind.

Wetlands worldwide continue to disappear, drained to create shoreline communities for people and filled to increase cropland. The lower 48 United States lost 53% of their wetlands between the 1700s and mid-1980s. Such losses destroy major fish and shellfish nurseries, natural flood and pollution control, and habitat for countless plants and animals.

The mosaic of habitats in, on, or near the seafloor – home to 98% of all marine species – is also being decimated. Like clear-cutting of an old-growth forest, the use of large, heavy trawls dragged along the sea bottom to catch groundfish and other species flattens and simplifies complex, structured habitats such as gravels, coral reefs, crevices, and boulders and drastically reduces biodiversity. Studies reported on by the National Research Council of the US National Academy of Sciences have shown that a single tow can injure or destroy upward of two-thirds of certain bottom-dwelling species, which may still not have recovered after a year or more of no trawling.

Habitat fragmentation and destruction, whether on land or in freshwater and marine environments, may lead directly to extinction or isolate organisms in ways that make them extremely vulnerable to natural disturbances, climate change, or further human disturbance.

Biotic homogenization

"The one process ongoing … that will take millions of years to correct," Wilson (1994, p. 355) admonishes us, "is the loss of genetic and species diversity by the destruction of natural habitats. This is the folly our descendants are least likely to forgive us." Both deliberately and inadvertently, humans are rearranging Earth's living components, reducing diversity and homogenizing biotas around the world. The present continuing loss of genetic diversity, of populations, and of species vastly exceeds background rates. At the same time, our global economy is transporting species worldwide at unprecedented scales.

The globe is now experiencing its sixth mass extinction, the largest since the dinosaurs vanished 65 Ma; present extinction rates are thought to be on the order of 100–1000 times those before people dominated Earth. According to the Millennium Ecosystem Assessment (2005), a 5-year project begun in 2001 to assess the world's ecosystems, an estimated 10–15% of the world's species will be committed to extinction by 2035. Approximately 20% of all vertebrates, including 33% of sharks and rays, are at risk of extinction.

At least one of every eight plant species is also threatened with extinction. Although mammals and birds typically receive the most attention, massive extinctions of plants, which form the basis of the biosphere's food webs, undermine life-support foundations. Mutualistic relationships between animals and plants, particularly evident in tropical forests, mean that extinctions in one group have cascading effects in other groups. Plants reliant on animals for pollination or seed dispersal, for example, are themselves threatened by the extinction of animal species they depend on. Not surprisingly, some scientists view extinction as the worst biological tragedy, but extinction is just another symptom of global biotic impoverishment.

Ever since they began to spread over the globe, people have transported other organisms with them, sometimes for food, sometimes for esthetic reasons, and most often accidentally. With the mobility of modern societies and today's especially speedy globalization of trade, the introduction of alien species has reached epidemic proportions, causing some scientists to label it biological pollution. Aliens are everywhere: in North America, zebra mussels and tamarisks, or saltcedar; in the Mediterranean Sea, the Red Sea sea jelly and the common aquarium alga *Caulerpa taxifolia*; and in the Black Sea, Leidy's comb jelly of northeastern America, to name just a few.

The costs of such invasions, in both economic and ecological terms, are high. In the United States, for example, annual economic losses due to damage by invasive species or the costs of controlling them exceed $137 billion per year – $40 billion more than the nation's losses from weather-related damage in 2005, when massive Hurricane Katrina devastated the Gulf Coast. Usually, aliens thrive and spread at the expense of native species, often causing extinctions. On many islands, more than half the plant species are not native, and in many continental areas the figure reaches 20% or more. Introduced species are fast catching up with habitat fragmentation and destruction as the major engines of ecological deterioration.

In addition, people have been modifying their crop plants and domesticated animals for 10,000 years or so – selecting seeds or individuals and breeding and cross-breeding them. The goal was something better, bigger, tastier, hardier, or all of the above. Success was sometimes elusive, but crop and livestock homogenization resulted, as did a loss of biodiversity among plant and animal foods. Of the myriad strains of potatoes domesticated by South American cultures, for example, only one was accepted and cultivated when potatoes first reached Europe. The new crop made it possible to feed more people from an equivalent area of land and initially staved off malnutrition. But the strain succumbed to a fungal potato blight in the 1800s. Had more than one strain been cultivated, the tragic Irish potato famines might have been averted. Today, as Sethi (2015) notes in *Bread, Wine, Chocolate*, we not only run the risk of losing the diversity enabling crops and livestock to resist pests, drought, disease, and inexorable changes in their environment, but we also risk losing the foods we love.

Genetic engineering

Although people have been breeding organisms for thousands of years, in the last few decades of the 20th century, they began to manipulate genes directly. Using tools of molecular biotechnology, scientists have cloned sheep and cows from adult body cells. New gene-editing technologies, called gene drives, have opened the potential to transform or eliminate entire species in the wild. US farmers routinely plant their fields with corn whose genetic material incorporates a bacterial gene resistant to certain pathogens. More than 40 genetically altered crops have been approved for sale to US farmers since 1992, with genes borrowed from bacteria, viruses, and insects. The United States accounts for nearly two-thirds of biotechnology crops planted globally. Worldwide in 2013, 174 million hectares in 24 countries on six continents were planted with genetically modified crops, as compared with 1.7 million hectares in 6 countries in 1996 – a 100-fold areal expansion in less than two decades.

Biotechnologists focus on the potential of this new-millennium green revolution to feed the growing world population, which has added more than 1 billion people in the past decade alone. But other scientists worry about unknown human and ecological health risks. These concerns have stirred deep scientific and public debate, especially in Europe, akin to the debate over pesticides in Rachel Carson's time.

One worrisome practice is plant genetic engineers' technique of attaching the genes they want to introduce into plants to an antibiotic-resistant gene. They can then easily select plants that have acquired the desired genes by treating them with the antibiotic, which kills any nonresistant plants. Critics worry that the antibiotic-resistant genes could spread to human pathogens and worsen an already growing antibiotic-resistance problem. Another concern arises from allergies humans might have or develop in response to genetically modified foods.

Although supporters of genetic engineering believe that genetically altered crops pose few ecological risks, ecologists have raised a variety of concerns. Studies in the late 1990s indicated that pollen from genetically engineered Bt corn can kill monarch butterfly caterpillars. Bt is a strain of bacterium that has been used since the 1980s as a pesticidal spray; its genes have also been inserted directly into corn and other crops. Ecologists have long worried that genetically engineered plants could escape from fields and crossbreed with wild relatives. Studies in radishes, sorghum, canola, and sunflowers found that genes from an engineered plant could jump to wild relatives through interbreeding. The fear is that a gene conferring insect or herbicide resistance might spread through wild plants, creating invasive superweeds that could potentially lower crop yields and further disturb natural ecosystems.

In fact, herbicide-resistant turf grass tested in Oregon in 2006 did escape and spread; transgenic canola has also been appearing throughout the US state of North Dakota, which has tens of thousands of hectares in conventional and genetically modified canola. According to the scientists who discovered the transgenic escapees growing in North Dakota – far from any canola field – the plants are likely to be cross-pollinating in the wild and swapping introduced genes; the plants' novel gene combinations indicate that the transgenic traits are stable and evolving outside of cultivation.

Genetically engineered crops do confer some economic and environmental benefits: for farmers, higher yields, lower costs, savings in management time, and gains in flexibility; for the environment, indirect benefits from using fewer pesticides and herbicides. But it is still an open question whether such benefits outweigh potential ecological risks or whether the public will embrace having genetically modified foods as dietary staples.

Direct Degradation of Human Life

Human biotic impacts are not confined to other species; human cultures themselves have suffered from the widening circles of indirect and direct effects people have imposed on the rest of nature. Over the past hundred years, human technology has worked both ways with regard to public health, for example. Wonder drugs controlled common pathogens at the same time that natural selection strengthened those pathogens' ability to resist the drugs. Reservoirs in the tropics made water supplies more reliable for people but also created ideal environments for human parasites. Industrialization exposed society to a remarkable array of toxic substances.

Although man's inhumanity to man has been both fact and subject of discourse for thousands of years, the discussions have mostly been removed from any environmental context. Few people today regard social ills as environmental impacts or humans as part of a biota. But diminished societal well-being – whether manifest in high death rates or poor quality of life – shares many of its roots with diminished nonhuman life as a form of biotic impoverishment.

Emerging and reemerging diseases

The intersection of the environment and human health is the core of the discipline known as environmental health. Among the environmental challenges to public health are direct effects of toxic chemicals; occupational health threats, including exposures to hazardous materials on the job; sanitation; and disposal of hazardous wastes.

Exploitation of nonrenewable natural resources – including coal mining, petroleum extraction and refining, and rock quarrying or other mining operations – often chronically impairs workers' health and shortens their lives. Farmworkers around the world suffer long-term ills from high exposures to pesticides and herbicides. Partly because of increased air pollution, asthma rates are rising, especially in big cities. Synthetic volatile solvents are used in products from shoes to semiconductors, producing lung diseases and toxic wastes. Nuclear weapons production starting in World War II, and associated contamination, have been linked to a variety of illnesses, including syndromes neither recognized nor understood at the time and whose causes were not diagnosed until decades afterward. The grayish metal beryllium, for example, was used in weapons production and was found decades later to scar the lungs of workers and people living near toxic waste sites.

Disease has challenged people throughout history. Infectious diseases – a significant fraction of which originated in wildlife or domestic animals – have played an especially significant role in human evolution and cultural development over the past 10,000 years. "Diseases represent evolution in progress," explains Diamond (1997), as microbes adapt from one host to another, one transmission vector to another. Quammen (2012, p. 20), writing in *Spillover*, puts it this way: "Infectious disease is a kind of natural mortar binding one creature to another … within the elaborate biophysical edifices we call ecosystems." Advances in 20th-century medicine, particularly immunization and sanitation, brought major successes in eradicating infectious diseases such as smallpox, polio, and many waterborne illnesses. But toward the century's end, emerging and reemerging afflictions were again reaching pandemic proportions. Infectious diseases thought to be on the wane – including tuberculosis, malaria, cholera, diphtheria, leptospirosis, encephalitis, and dengue fever – began a resurgence.

Even more troubling, seemingly new plagues – Ebola virus, hantavirus, HIV/AIDS, West Nile virus, the tick-borne bacterium causing Lyme disease, and the viruses behind chikungunya and Zika virus disease – are also spreading. Several of these come from wild animal hosts and pass to humans as people encroach further upon previously undisturbed regions. Quammen (2012) examines a number of such zoonoses – diseases arising when a pathogen leaps from a nonhuman animal to a person and sickens or kills that person – and highlights the complex connections between biodiversity and new zoonotic diseases. Biodiversity loss often increases disease transmission, as in Lyme disease and West Nile fever, but diverse ecosystems also serve as sources of pathogens. Overall, however, a number of studies since 2000 indicate that preserving intact ecosystems and their endemic biodiversity tends to hold down infection rates.

Human migrations – including their modern incarnation through air travel – also accelerate pathogen traffic and launch global pandemics, such as the 2003 outbreak of severe acute respiratory syndrome and the 2009 swine flu outbreak caused by the H1N1 virus. Even something as simple and apparently benign as lighting can become an indirect agent of disease. Artificial lighting, especially in the tropics, for example, can alter human and insect behavior in ways that speed transmission of insect-borne diseases, such as Chagas's disease, malaria, and leishmaniasis.

In addition, especially in highly developed countries, diseases attributable to affluence, overconsumption, and stress are taking a toll. Over the 20th century in the United States, observe Montgomery and Biklé (2016, p. 189), chronic diseases that lack an infectious agent "overtook infectious diseases as the leading cause of death." Heart disease is the States' number one cause of death; overnutrition, obesity, and diabetes stemming from sedentary habits, particularly among children, are chronic and rising. One estimate put the share of US children considered overweight or obese at one in three. This rise in obesity rates has been stunningly rapid. As recently as 1980, just 15% of adults were obese; by 2008, 34% were obese. Two-thirds of Americans are now considered either overweight or obese. Even more startling, a new trend – unique to the United States – has emerged over the past decade. Economists Case and Deaton (2015) found rising death rates among poorly educated middle-aged white males from suicide, drug and alcohol poisoning, and liver diseases.

Still, note Montgomery and Biklé, of an estimated 10^{30} microbes on Earth, only a few are human pathogens. In contrast, some 1 million kinds of nonpathogenic microbes live in and on our bodies, collectively forming humanity's microbiome. Varied microbial communities inhabit every person's skin, eyes, mouth, intestines, and so on. These communities differ as much from one another as a tropical forest differs from a desert. Our microbial allies help regulate our major physiological systems, including the immune system. Recent genetic research, which identifies specific microbes and helps reveal the roles they play, has implicated disturbances of the human microbiome in diseases ranging from infection by the bacterium *Clostridium difficile* to autoimmune ills such as Crohn's disease. Perturbations of intestinal microbial communities may even influence obesity.

Loss of cultural diversity

Although not conventionally regarded as elements of biodiversity, human languages, customs, agricultural systems, technologies, and political systems have evolved out of specific regional environments. Like other organisms' adaptive traits and behaviors, these elements of human culture constitute unique natural histories adapted, as are other natural histories, to the biogeographical context in which they arose. Yet modern technology, transportation, and trade have pushed the world into a globalized culture, thereby reducing human biological and cultural diversity.

Linguists, for example, are predicting that at least half of the 7000 languages spoken today will become extinct in the 21st century. With the spread of Euro-American culture, unique indigenous human cultures, with their knowledge of local medicines and geographically specialized economies, are disappearing even more rapidly than the natural systems that nurtured them. This loss of human biodiversity is as much a cause for concern as the loss of nonhuman biodiversity.

Reduced quality of life

The effects of environmental degradation on human quality of life are another symptom of biotic impoverishment. Food availability, which depends on environmental conditions, is a basic determinant of quality of life. Yet according to the World Health Organization, nearly half the world's population suffers from one of two forms of poor nutrition: undernutrition or overnutrition. A big belly is now a symptom shared by malnourished children, who lack calories and protein, and overweight residents of the developed world, who suffer clogged arteries and heart disease from eating too much.

Independent of race or economic class, declining quality of life in today's world is manifest in symptoms such as cancers in the United States caused by environmental contaminants and the high disease rates in the former Soviet Bloc after decades of unregulated pollution. Even with explicit legal requirements that industries release information on their toxic emissions, many people throughout the world still lack both the information and the decision-making power that would give them any control over the quality of their lives.

Aggrieved about the degraded environment and resulting quality of life in his homeland, Ogoni activist Ken Saro-Wiwa issued a statement shortly before he was executed by the Nigerian government in 1995, saying, "The environment is man's first right. Without a safe environment, man cannot exist to claim other rights, be they political, social, or economic." Kenyan Maathai (2009, p. 249), 2004 winner of the Nobel Peace Prize, has also written, "[I]f we destroy it, we will undermine our own ways of life and ultimately kill ourselves. This is why the environment needs to be at the center of domestic and international policy and practice. If it is not, we don't stand a chance of alleviating poverty in any significant way."

Having ignored this kind of advice for decades, nations are seeing a new kind of refugee attempting to escape environmental degradation and desperate living conditions; the number of international environmental refugees exceeded the number of political refugees around the world for the first time in 1999. Environmental refugees flee homelands devastated by flooding from dam building, extraction of mineral resources, desertification, and unjust policies of national and international institutions. Such degradation preempts many fundamental human rights, including the rights to health, livelihood, culture, privacy, and property.

People have long recognized that human activities that degrade environmental conditions threaten not only the entire biosphere but also human quality of life. As early as 4500 years ago in Mesopotamia and South Asia, writings revealed an awareness of biodiversity, of natural order among living things, and of consequences of disrupting the biosphere. Throughout history, even as civilization grew increasingly divorced from its natural underpinnings, writers, thinkers, activists, and people from all walks of life have continued to see and extol the benefits of nature to humans' quality of life.

Contemporary society still has the chance to relearn how important the environment is to quality of life. It is encouraging that the United Steelworkers of America in 1990 released a report recognizing that protecting steelworker jobs could not be done by ignoring environmental problems and that the destruction of the environment may pose the greatest threat to their children's future. It is also encouraging that in 2007 the Nobel Peace Prize was awarded to a political figure and a group of scientists for their work on climate change.

Environmental injustice

Making a living from nature's wealth has consistently opened gaps between haves and have-nots, between those who bear the brunt of environmental damage to their homeplaces and those who do not, and between the rights of people alive now and those of future generations; these disparities too are part of biotic impoverishment. Inequitable access to "man's first right" – a healthy local environment – has come to be known as environmental injustice.

Environmental injustices, such as institutional racism, occur in industrial and nonindustrial nations. Injustice can be overt, as when land-use planners site landfills, incinerators, and hazardous waste facilities in minority communities, or when environmental agencies levy fines for hazardous waste violations that are lower in minority communities than in white communities. Less overt, but no less unjust is the harm done to one community when unsound environmental practices benefit another. Clear-cut logging in the highlands of northwestern North America, for example, benefits logging communities while damaging the livelihoods of lowland fishing communities subjected to debris flows, sedimentation, and downstream flooding.

Institutional racism and environmental injustice are usually acknowledged only after the fact, if at all. For example, in the US city of Flint, Michigan, the 2010 population was more than 60% black and Latino, and the 2014 median household income was 16% less than for the state as a whole. To save money, the struggling city in 2014 switched its water source from Lake Huron to the Flint River. But instead of saving money, the corrosive new water source leached lead out of the city's aging water pipes. Despite increasing evidence of serious health effects after the switch – including potentially lifelong brain damage among the city's children – Michigan's governor and other state officials for months assured citizens the water was safe. In a report issued in March 2016, an independent panel appointed by the governor stated that the facts "lead us to the inescapable conclusion that this is a case of environmental injustice" and that "Flint residents, who are majority black or African-American and among the most impoverished of any metropolitan area in the United States, did not enjoy the same degree of protection from environmental and health hazards as that provided to other communities."

The plight of the working poor and disparities between rich and poor are themselves examples of biotic impoverishment within human society. According to the United Nations Research Institute for Social Development, in 1994 the collective wealth of the world's 358 billionaires equaled the combined income of the poorest 2.4 billion people. In 2010, *Forbes Magazine* put the number of billionaires at 1011, with a total worth of $3.6 trillion. By 2015, the number of billionaires had climbed to 1826, and their total worth had practically doubled, to $7.05 trillion – more than twice the gross domestic product (GDP) of Germany, Europe's most prosperous country.

In the United States during the last decade of the 20th century, the incomes of poor and middle-class families stagnated or fell, despite a booming stock market. The Center on Budget and Policy Priorities and the Economic Policy Institute reported that between 1988 and 1998, earnings of the poorest fifth of American families rose less than 1%, while earnings of the richest fifth jumped 15%. By the middle of the second decade of the 21st century, the disparity in wealth among Americans had become the widest among industrialized nations, with the wealthiest 3% of the population holding 54% of the wealth. The wealthiest Americans continue to prosper, even during and after the global recession of 2008, while the less well-off keep losing ground.

But perhaps the grossest example of human and environmental domination leading to continued injustice is the creation of a so-called third world to supply raw materials and labor to the dominant European civilization after 1500 and the resulting schism between today's developed and developing nations. Developing regions throughout the world held tremendous stores of natural wealth, some of it – like petroleum – having obvious monetary value in the dominant economies and some having a value invisible to those economies – like vast intact ecosystems. A 2010 United Nations study carried out under the Economics of Ecosystems and Biodiversity Initiative estimated that even today, Earth's ecosystems account for roughly half to 90% of the source of livelihoods for rural and forest-dwelling peoples; the study calls this value the GDP of the poor.

Dominant European civilizations unabashedly exploited this natural wealth and colonized or enslaved the people in whose homelands the wealth was found. But the dominant civilizations also exported their ways of thinking and their economic models to the developing world, not only colonizing places but also effecting what Maathai called a colonization of the mind. Although dominant 21st-century society tends to dismiss ancient wisdom as irrelevant in the modern world, perhaps the cruelest impoverishment of all is the cultural and spiritual deracination experienced by exploited peoples worldwide.

Exploitation of poor nations and their citizens by richer, consumer countries – and in many cases by the same governments that fought for independence from the colonists while adopting the colonists' attitudes and economic models – persists today in agriculture, wild materials harvesting, and textile and other manufacturing sweatshops. In the mid-1990s, industrial countries consumed 86% of the globe's aluminum, 81% of its paper, 80% of its iron and steel, 75% of its energy, and 61% of its meat; they are thus responsible for most of the environmental degradation associated with producing these goods. Most of the actual degradation, however, still takes place in developing nations.

As a result, continuing environmental and social injustice, perpetrated by outsiders and insiders alike, pervades developing nations. Such impoverishment can take the form of wrenching physical dislocation like the massive displacements enforced by China's Three Gorges Dam. It can appear as environmental devastation of homelands and murder of the people who fought to keep their lands, as in the Nigerian government–backed exploitation of Ogoniland's oil reserves by the Shell Petroleum Development Corporation. After Saro-Wiwa's execution, the Ogoni were left, without a voice, to deal with a scarred and oil-polluted landscape.

Poverty still plagues women and children, despite great advances in the welfare of both groups over the past century. Children from impoverished communities, even in affluent nations, suffer from the lethargy and impaired physical and intellectual development known as failure to thrive. Poverty forces many children to work the land or in industrial sweatshops; lack of education prevents them from attaining their intellectual potential. This impoverishment in the lives of women and children is as much a symptom of biotic impoverishment as are deforestation, invasive alien organisms, or species extinctions.

Little by little, community-based conservation and development initiatives are being mounted by local citizens to combat this impoverishment: Witness Maathai's Green Belt Movement, which began with tree planting to restore community landscapes and offer livelihoods for residents, and the rise of ecotourism and microlending (small loans made to individuals, especially women, to start independent businesses) as ways to bring monetary benefits directly to local people without further damaging their environments. Ultimately, one could see all efforts to protect the ethnosphere and biosphere as a fight for the rights of future generations to an environment that can support them.

Political instability

Only during the last two decades of the 20th century did environmental issues find a place on international diplomatic agendas, as scholars began calling attention to – and governments began to see – irreversible connections between environmental degradation and national security. British scholar Myers (1993), noting that environmental problems were likely to become predominant causes of conflict in the decades ahead, was one of the first to define a new concept of environmental security. National security threatened by unprecedented environmental changes irrespective of political boundaries will require unprecedented responses altogether different from military actions, he warned. Nations cannot deploy their armies to hold back advancing deserts, rising seas, or the greenhouse effect. Increasingly, governments have begun to acknowledge such threats. In just one recent example, US diplomatic, defense, and intelligence agencies have repeatedly cited climate change as an urgent and growing threat to national security.

Canadian scholar Homer-Dixon (1999) showed that environmental scarcities – whether created by ecological constraints or sociopolitical factors including growing populations, depletion of renewable resources such as fish or timber, and environmental injustice perpetrated by one segment of a population on another – were fast becoming a permanent, independent cause of civil strife and ethnic violence. He found that such scarcity was helping to drive societies into a self-reinforcing spiral of dysfunction and violence, including terrorism. Environmental and economic injustices worldwide leave no country immune to this type of threat.

Typically, diplomacy has stalled in conflicts over natural resources: arguments over water rights have more than once held up Israeli-Palestinian peace agreements; fights over fish erupted between Canada and the United States, Spain, and Portugal. In contrast, in adopting the Montreal Protocol on Substances That Deplete the Ozone Layer in 1987, governments, nongovernmental organizations, and industry successfully worked together to safeguard part of the environmental commons. The treaty requires signatory nations to decrease their use of CFCs and other ozone-destroying chemicals and has been, according to former United Nations secretary general Kofi Annan, perhaps the most successful international agreement to date.

Cumulative effects

If scientists have learned anything about the factors leading to biotic impoverishment, they have learned that the factors' cumulative effects can take on surprising dimensions. As scholars like Fagan (1999) and Diamond (2005) have detailed, the multiple stresses of global climatic cycles such as El Niño, natural events like droughts or floods, resource depletion, and social upheaval have shaped the fates of civilizations.

Societies as far-flung as ancient Egypt, Peru, the American Southwest, and Easter Island prospered and collapsed because of unwise management of their environments. The city of Ubar, built on desert sands in what is now southern Oman, vanished into the sinkhole created by drawing too much water out of its great well. In modern Sahelian Africa, a combination of well digging and improved medical care and sanitation led to a threefold population increase. The combined effects of higher population density and a sedentary way of life exceeded local areas' capacity to sustain people and their livestock, especially in the face of high taxes levied by colonial governments. As a result, impoverished societies took the place of nomadic cultures that had evolved and thrived within the desert's realities.

During the first decades of the 21st century, numerous natural disasters befell nations around the world: wildfires in Australia, Bolivia, Canada, Russia, and the United States; flooding in the British Isles, China, India, Romania, and West Africa; devastating hurricanes and typhoons in the Caribbean, Philippines, Taiwan, and southeastern United States; catastrophic landslides and floods in China, Guatemala, Pakistan, and Portugal; and destructive earthquakes in Chile, China, Haiti, Indonesia, Japan, and Pakistan. Neither the rains nor the earthquakes were caused by human activity, but the cumulative effects of human land uses and management practices – from dikes separating the Mississippi from its floodplain to deforestation in Haiti – made the losses of human life and property much worse than they might have been otherwise.

Root Causes of Human Impact

The ultimate cause of humans' massive environmental impact is our individual and collective reproductive and consumptive behavior, which has given us spectacular success as a species. But the very things that have enabled people to thrive in nearly every environment have magnified our impacts on those environments, and the technological and political steps we take to mitigate our impacts often aggravate them. Too many of us simply take too much from the natural world and ask it to absorb too much waste.

Fragmented Worldviews, Fragmented Worlds

For most of human history, people remained tied to their natural surroundings. Even as agriculture, writing, and technology advanced, barriers of geography, language, and culture kept people a diverse lot, each group depending on mostly local and regional knowledge about where and when to find resources necessary for survival. Their worldviews, and resulting economies, reflected this dependency.

For example, in northwestern North America starting about 3000 years ago, a native economy centered on the abundance of Pacific salmon. At its core was the concept of the gift and a belief system that treated all parts of the Earth – animate and inanimate – as equal members of a community. In this and other ancient gift economies, a gift was not a possession that could be owned; rather, it had to be passed on, creating a cycle of obligatory returns. Individuals or tribes gained prestige through the size of their gifts, not the amount of wealth they accumulated.

This system coevolved with the migratory habits of the salmon, which moved en masse upriver to spawn each year. Because the Indians viewed salmon and themselves as equals in a shared community, killing salmon represented a gift of food from salmon to people. Fishers were obligated to treat salmon with respect or risk losing this vital gift. The exchange of gifts between salmon and humans – food for respectful treatment – minimized waste and overharvest and ensured a continuous supply of food. Further, the perennial trading of gifts among the people effectively redistributed the wealth brought each year by fluctuating populations of migrating fish, leveling out the boom-and-bust cycles that usually accompany reliance on an uncertain resource.

In modern times, the gift economy, along with the egalitarian worldview that accompanied it, has been eclipsed by a redistributive economy tied not to an exchange of gifts with nature but to the exploitation of nature and to technologies enhancing that exploitation. Instead of viewing natural resources as joint members in a shared community, people came to view them as commodities. Natural resources fell under the heading of "land" in an economic trinity comprising three factors of production: land, labor, and capital. Land and resources, including crops, were seen as expendable or easily substitutable forms of capital whose value was determined solely by their value in the human marketplace.

In 1776 Adam Smith published his famous *Inquiry Into the Nature and Causes of the Wealth of Nations*, in which he argued that society is merely the sum of its individuals, that social good is the sum of individual wants, and that the market (a so-called invisible hand) automatically guides individual behavior to common good. Crucial to his theories were division of labor and the idea that all factors of production were freely mobile. His mechanistic views created an economic rationale for no longer regarding individuals as members of a community linked by ethical, social, and ecological bonds.

About the same time, fueling and fueled by the beginnings of the Industrial Revolution, the study of the natural world was morphing into modern physics, chemistry, geology, and biology. Before the mid-19th century, those who studied the natural world – early 19th-century German biogeographer Baron Alexander von Humboldt and his disciple Charles Darwin among them – took an integrated view of science and nature, including people. Both scientists regarded understanding the complex interdependencies among living things as the noblest and most important result of scientific inquiry.

But this integrated natural philosophy was soon supplanted by more atomistic views, which fit better with industrialization. Mass production of new machines relied on division of labor and interchangeable parts. Like automobiles on an assembly line, natural phenomena were broken down into their supposed component parts in a reductionism that has dominated science ever since. Rushing to gain in-depth, specialized knowledge, science and society lost sight of the need to tie this knowledge together. Disciplinary specialization replaced integrative scholarship.

Neoclassical economics, which arose around 1870, ushered in the economic worldview that rules today. A good's value was no longer tied to the labor required to make it but derived instead from its scarcity. A good's price was determined only by the interaction of supply and demand. As part of "land," natural resources therefore became part of the human economy, rather than the material foundation making the human economy possible. Because of its doctrine of infinite substitutability, neoclassical economics rejects any limits on growth; forgotten are classical economic thinkers and contemporaries of von Humboldt, including Thomas Malthus and John Stuart Mill, who saw limits to growth of the human population and material well-being.

Consequently, the 19th and 20th centuries saw the rise to dominance of economic indicators that fostered the economic invisibility of nature – misleading society about the relevance of Earth's living systems to human well-being. Among the worst indicators are gross national product (GNP) and its cousin, GDP. GNP measures the value of goods and services generated by a nation's citizens or companies, regardless of their location around the globe. GDP, in contrast, measures the value of goods and services produced within a country's borders, regardless of who or what generates those goods and services.

In effect, both GNP and GDP measure money changing hands, no matter what the money pays for; they make no distinction between what is desirable and undesirable, between costs and benefits. Both indicators ignore important aspects of the economy like unpaid work or nonmonetary contributions to human fulfillment – parenting, volunteering, checking books out of the library. Worse, the indicators also omit social and environmental costs, such as pollution, illness, or resource depletion; they only add and do not subtract. GDP math adds in the value of paid daycare or a hospital stay and ignores the value of unpaid parenting or care given at home by family or friends. It adds in the value of timber sold but fails to subtract the losses in biodiversity, watershed protection, or climate regulation when a forest is cut.

Over the past few decades, efforts have been made to create less blinkered economic indicators. Social scientists Herman Daly and John Cobb in 1989 developed an index of sustainable economic welfare, which adjusts the United States' GNP by adding in environmental good things and subtracting environmental bad things. Public expenditures on education, for example, are weighted as "goods," while costs of pollution cleanup, depletion of natural resources, and treating environment-related illnesses are counted as "bads." Unlike the soaring GDP of recent decades, this index of sustainable economic welfare remained nearly unchanged over the same period.

Still other work aims to reveal nature's worth in monetary terms by assigning dollar values to ecological goods and services. A 1997 study by ecologist David Pimentel and colleagues calculated separate values for specific biological services, such as soil formation, crop breeding, or pollination. By summing these figures, these researchers estimated the total economic benefits of biodiversity for the United States at $319 billion – 5% of US GDP at the time – and for the world at $2928 billion. A 2000 analysis by Pimentel and colleagues reported that the approximately 50,000 nonnative species in the United States cause major environmental damage and reparation costs amounting to $137 billion a year.

As part of the United Nations International Year of Biodiversity in 2010, several studies translated the value of the world's ecosystems into dollar values. One report estimated the worth of crucial ecosystem services delivered to humans by living systems at $21 trillion to $72 trillion per year – comparable to a world gross national income of $58 trillion in 2008. Another study reported that as many as 500 million people worldwide depend on coral reefs – valued between $30 billion and $172 billion a year – for fisheries, tourism, and protection from ocean storms and high waves, services threatened by warmer and more acidic seas.

Although a monetary approach does not create a comprehensive indicator of environmental condition, it certainly points out that ecological values ignored by the global economy are enormous. Consequently, several countries and a growing number of global financial institutions, such as the World Bank, have begun to include natural capital in their economic accounting systems. More than 30 countries have begun natural capital accounting using a standard methodology adopted by the UN Statistical Commission in 2012, and many financial institutions around the world have pledged to consider natural capital in private-sector accounting and decision making.

Too Many Consuming Too Much

From the appearance of *H. sapiens* about 200,000 years ago, it took the human population until 1804 to reach its first billion, 123 years to double to 2 billion, and 33 years to achieve 3 billion. Human population doubled again from 3 billion to 6 billion in about 40 years – before most post–World War II baby boomers reached retirement age. Even with fertility rates declining in developed countries, China, and some developing countries where women are gaining education and economic power, and with pandemics like AIDS claiming more lives, the US Census Bureau predicts that world population will reach 9 billion by 2044.

People appropriate about 40% of global plant production, 54% of Earth's freshwater runoff, and enough of the ocean's bounty to have depleted 63% of assessed marine fish stocks. In energy terms, one person's food consumption amounts to 2500–3000 cal a day, about the same as that of a common dolphin. But with all the other energy and materials humans use, global per capita energy and material consumption has soared even faster than population growth over the past 50 years. Now, instead of coevolving with a natural economy, global society is consuming the foundations of that economy, impoverishing Earth's living systems and undermining the foundations of its own existence (**Fig. 1**; Karr, 2008).

Measuring Environmental Impacts

For most of the 20th century, environmental measurements, or indicators, tracked primarily two classes of information: counts of activities directed at environmental protection and the supply of products to people. Regulatory agencies are typically preoccupied with legislation, permitting, or enforcement, such as the numbers of environmental laws passed, permits issued, enforcement actions taken, or treatment plants constructed. Resource protection agencies concentrate on resource harvest and allocation. Water managers, for example, measure water quantity; they allocate water to domestic, industrial, and agricultural uses but seldom make it a priority to reserve supplies for sustaining aquatic life, to protect scenic and recreational values, or simply to maintain the water cycle. Foresters, farmers, and fishers count board-feet of timber, bushels of grain, and tons of fish harvested. Governmental and nongovernmental organizations charged with protecting biological resources keep counts of threatened and endangered species.

As in the parable of the three blind men and the elephant – each of whom thinks the elephant looks like the one body part he can touch – these or similar indicators measure only one aspect of environmental quality. Counting bureaucratic achievements

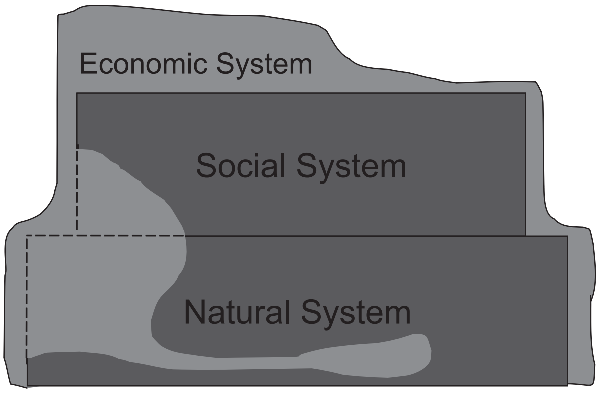

Fig. 1 Relationships among the natural, social, and economic systems on Earth. Human economies may be thought of as icing atop a two-layer cake. The economic icing is eroding the human social and natural layers beneath it, threatening the foundation and sustainability of all three systems. Modified from Karr, J.R., 2008. Attaining a sustainable society. In: Westra, L, Bosselmann, K., Westra, R. (Eds.), Reconciling Human Existence With Ecological Integrity, pp. 21–37. London: Earthscan.

Table 2 Plausible indicators of environmental quality[a]

Indirect depletion of living systems through alterations in physical and chemical environments
1. Degradation of water: chemical contaminant concentrations, river flows, rainfall, runoff, changing water temperatures
2. Soil depletion: erosion rates, desertification rates, salt accumulation in soils
3. Chemical contamination: pollutant and toxic emissions; pollutant and toxic concentrations in air, water, soil, and living organisms
4. Altered biogeochemical cycles: river flows and lake levels; quantity of nutrients going into water bodies, or nutrient loading; nutrient concentrations in water bodies; chlorophyll concentrations, reflecting nutrient-triggered algal blooms, in water bodies; oxygen depletion in water bodies; trophic status of lakes; changes in air and soil chemistry; atmospheric greenhouse gas concentrations
5. Global climate change: atmospheric greenhouse gas concentrations, change in atmospheric temperatures, distribution and intensity of severe storms or droughts, rate of glacial retreat, change in mean tidal heights

Direct depletion of nonhuman life
1. Overharvest of renewable resources such as fish and timber: tons of fish harvested; for a given anadromous fish population, number of adult fish returning to rivers to spawn; hatchery fish released and recovered; board-feet of timber harvested; forest regrowth rates; quantity of standing timber; ecological footprints
2. Habitat fragmentation and destruction: area of remaining grassland, wetland, and other habitats; landscape connectivity; rates of habitat destruction
3. Biotic homogenization: number of extinct, threatened, and endangered taxonomic groups; spread of nonnative species; local or regional diversity; diversity among cultivated crops and livestock; damage and reparation costs due to invasions or extinctions; major relocations in species distributions
4. Genetic engineering: genetic diversity within strains, escape of genetically engineered organisms or traits to wild populations

Direct degradation of human life
1. Emerging and reemerging diseases: death or infection rates caused by diseases, including diseases of affluence; geographic spread of diseases; recovery rates; frequency and spread of resistance to antibiotics and other drugs
2. Loss of cultural diversity: incidence of ethnic and cultural cleansings, extinction of cultures, death of languages
3. Reduced quality of life: population size and growth; starvation, malnutrition, and obesity rates; infant mortality rates; teen pregnancy rates; literacy rates; suicide rates and other measures of stress; length of work week; child or other forced labor; changes in death rates or average life spans
4. Environmental injustice: siting of toxic waste dumps or waste emissions relative to resident communities, economic exploitation of certain groups, worker strikes, wage and income gaps, unemployment rates for different economic sectors
5. Political instability: frequency of domestic and international strife, terrorism rates, number of refugees, genocide
6. Cumulative effects: frequency of catastrophic natural disasters; costs of weather-related property damage; human death tolls; government subsidies of environmentally destructive activities, as in fishery overcapitalization, below-cost timber sales, water projects, and agricultural price supports; replacement costs for ecological services; pricing that reflects environmental costs; "green" taxes; rise in polycultural agricultural practices; number of organic farms

[a]These indicators have been or could be used to monitor status and trends in environmental quality in ways that capture the many faces of biotic impoverishment.

focuses on activities rather than on information about real ecological status and trends. Measurements of resource supply keep track of commodity production, not necessarily a system's capacity to continue supplying that commodity. And measuring only what we remove from natural systems – as if we were taking out the interest on a savings account – overlooks the fact that we are usually depleting principal as well.

Even biologists' counts of threatened and endangered species, which would seem to measure biotic impoverishment directly, still focus narrowly on biological parts, not ecological wholes. Enumerating threatened and endangered species is just like counting any other commodity. It brings our attention to a system already in trouble, perhaps too late. And it subtly reinforces our view that we know which parts of the biota are most important.

Society needs to rethink its use of available environmental indicators, and it needs to develop new indicators that represent current conditions and trends in the systems humans depend on (**Table 2**). It particularly needs objective measures more directly tied to the condition, or health, of the environment so that people can judge whether their activities are compromising that condition.

Such measures should be quantitative, yet easy to understand and communicate; they should be cost-effective and applicable in many circumstances. Unlike narrow criteria tracking only administrative, commodity, or endangered species numbers, they should give reliable signals about status and trends in ecological systems. Ideally, effective indicators should describe the present condition of a place, aid in diagnosing the underlying causes of that condition, and make predictions about future trends. They should reveal not only risks from present activities but also potential benefits from alternative management decisions.

Most important, these indicators should, either singly or in combination, give information explicitly about living systems. Measurements of physical or chemical factors can sometimes act as surrogates for direct biological measurements, but only when the connection between those measures and living systems is clearly understood. Too often we make assumptions that turn out to be wrong and fail to protect living systems – for example, when water managers assume that chemically clean water equals a healthy aquatic biota. Without a full spectrum of indicators – and without coupling them to direct measures of biological condition – only a partial view of the degree of biotic impoverishment can emerge.

General Sustainability Indexes

As environmental concerns have become more urgent – and governmental and nongovernmental organizations have struggled to define and implement the concept of sustainable development – the effort has grown to create indicator systems that explicitly direct the public's and policymakers' attention to the value of living things. Moving well past solely economic indexes like GDP, several indexes have been developed to integrate ecological, social, and economic well-being.

The index of environmental trends for nine industrialized countries, developed by the nonprofit National Center for Economic and Security Alternatives, incorporated ratings of air, land, and water quality; chemical and waste generation; and energy use since 1970. By its 1995 rankings, environmental quality in the United States had gone down by 22% since 1970, while Denmark had declined by 11%.

In 2000, world leaders, supported by the United Nations Development Programme, defined a set of eight millennium development goals to be attained by 2015, which combine poverty, education, employment, and environmental sustainability. They include human rights and health goals – such as universal primary education, gender equality, and combating AIDS and other diseases – as well as goals to promote environmental sustainability. Since the program began, the agency reported in 2015, global poverty has been halved, with fewer than 850 million people – but 40% of the population in sub-Saharan Africa – still living in extreme poverty. By 2015, about 91% of the world's population had access to improved drinking water sources (piped or not coming from unprotected wells, springs, or surface water), and remarkable progress had been made in fighting malaria and tuberculosis and in reducing the proportion of slum dwellers in the metropolises of the developing world. But environmental sustainability remains under severe threat, as global carbon emissions escalate, forests are felled, and fish stocks are overexploited. Nonhuman species are hurtling toward extinction faster than ever, and health and education among poor people, and gender equality everywhere, still lag.

The environmental performance index was developed and first released in 2006 by Yale and Columbia universities to complement the United Nations' millennium development goals. It ranks how well countries do in protecting human health from environmental harm and in protecting ecosystems. The 2016 index ranks 180 countries on more than 20 performance indicators in 9 categories reflecting the twin goals of environmental health and ecosystem vitality. Environmental health is measured by such indicators as child mortality, air quality, and access to drinking water and sanitation; ecosystem vitality by metrics including trends in carbon emissions, protection of varied biotic systems, and wastewater treatment, among others. Top-performing nations for 2016 included Finland, Sweden, and Slovenia. The United States ranked 26th, having risen from 61st in 2010 but still well below much of Europe and Singapore.

Ecological Footprints

A resource-accounting approach pioneered in the 1990s by geographers Wackernagel and Rees (1996) translates humans' impact on nature, particularly resource consumption, into an ecological footprint. This accounting estimates the area required by a city, town, nation, or other human community to produce consumed resources and absorb generated wastes; it then compares the physical area occupied by that city or country with the area required to meet its needs. The 29 largest cities of Baltic Europe, for example, appropriate areas of forest, agricultural, marine, and wetland ecosystems that are at least 565–1130 times larger than the areas of the cities themselves.

According to the Global Footprint Network, national ecological footprints in 2010 ranged from a high of 10.7 ha per person for the United Arab Emirates to 0.4 ha per person for Timor-Leste and 0.6 for Afghanistan and Bangladesh. The United States' ecological footprint – 8.0 ha per person – tied for fourth among 152 nations with populations of at least 1 million. One hundred four of these nations operate under ecological deficits; that is, their consumption exceeds the biological capacity of their lands and waters to furnish needed resources and absorb their wastes. At their present rates of consumption, these nations are therefore overexploiting either their own resources or those of other nations.

By ecological footprint accounting, raising 7.5 billion people on Earth to living standards – and thus ecological footprints – equal to those in the United States would require at least three more planets than the only one we have. Clearly, humans are consuming more resources, and discarding more waste, than Earth's living systems can produce or absorb in a given time period. This gap is the global sustainability gap that lies before us.

Measuring the State of Living Systems

Most environmental indexes and accounting systems are still human centered; they do not measure the condition of the biota itself. We may know that biodiversity's services are worth huge sums of money and that our hometown's ecological footprint is much bigger than the town's physical footprint, but how do we know whether specific activities damage living systems or that other activities benefit them? How do we know if aggregate human activity is diminishing life on Earth? To answer this question, we need measures that directly assess the condition of the biota.

Biological assessment directly measures the attributes of living systems to determine the condition of a specific landscape. The very presence of thriving living systems – sea otters and kelp forests off the central California coast; salmon, orcas, and herring in Pacific Northwest waters; monk seals in the Mediterranean Sea – says that the conditions those organisms need to survive are also present. A biota is thus the most direct and integrative indicator of local, regional, or global biological condition. Biological assessments give us a way to evaluate whether monetary valuations, sustainability indexes, and ecological footprints are telling the truth about human impact on the biota. Biological assessments permit a new level of integration because living systems, including human cultures, register the accumulated effects of all forms of degradation caused by human actions.

Direct, comprehensive biological monitoring and assessment began in the last decades of the 20th century, when Karr (1981, 2006) devised the index of biological integrity (IBI) to assess the health of streams in the US Midwest. Over the next three decades, indexes built on IBI's principles were developed for other regions and other environments, including lakes, wetlands, coastal marine habitats, and terrestrial areas. IBI combines several indicators into a multimetric index, an approach it shares with economic indexes like the consumer price index or the index of leading economic indicators. Instead of prices of diverse consumer goods, however, IBI measures attributes of the flora and fauna living at a place. To date, the principles underpinning IBI have helped scientists, resource managers, and citizen volunteers understand, protect, and restore living systems in at least 70 countries worldwide.

The most widely used indexes for assessing rivers examine fishes and benthic (bottom-dwelling) invertebrates. These groups are abundant and easily sampled, and the species living in a water body represent a diversity of anatomical, ecological, and behavioral adaptations. As humans alter watersheds and waters, changes occur in taxonomic richness (biodiversity), species composition (which species are present), individual health, and feeding and reproductive relationships. The specific measurements for streams and rivers (**Table 3**) are sensitive to a broad range of human effects in waterways, such as sedimentation, nutrient enrichment, toxic chemicals, physical habitat destruction, and altered flows. The resulting index thus combines, and reflects, responses to human activities from a whole biological community – its parts, such as species, and its processes, such as food web dynamics.

Sampling the inhabitants of a stream tells us much about that stream and its landscape. Biological diversity is higher upstream of wastewater treatment plants than downstream, for example, whereas year-to-year variation at the same location is low (**Fig. 2**). Biological sampling also reveals differences between urban and rural streams. For instance, samples of invertebrates from one of the best streams in rural King County, in the US state of Washington, contain 27 kinds, or taxa, of invertebrates; similar samples from an urban stream in the city of Seattle contain only 7. The rural stream has 18 taxa of mayflies, stoneflies, and caddisflies; the urban stream, only 2 or 3. When these and other metrics are combined in an index based on invertebrates, the resulting benthic IBI (B-IBI) numerically ranks the condition, or health, of a stream (**Table 4**).

A benthic IBI can also be used to compare sites in different regions. Areas in Wyoming's Grand Teton National Park where human visitors are rare have near-maximum B-IBIs. Streams with moderate recreation taking place in their watersheds have B-IBIs that are not significantly lower than those without human presence, but places where recreation is heavy are clearly damaged. Urban streams in the nearby town of Jackson are even more degraded but not as bad as urban streams in Seattle.

Nation-specific biological assessments also can be and are being done. The US Environmental Protection Agency, for example, in 2006 performed a nationwide survey of stream condition using an IBI-like multimetric index. The survey found that 28% of US stream miles were in good condition in comparison with least-disturbed reference sites in their regions, 25% were in fair condition, and 42% were in poor condition (5% were not assessed). The agency has been expanding this effort to include other water resource types, including coastal waters, coral reefs, lakes, large rivers, and wetlands.

Since 2000, the Heinz Center (2008) has published two editions of its report on the state of US ecosystems, which seeks to capture a view of the large-scale patterns, conditions, and trends across the United States. The center defined and compiled a select set of indicators – specific variables tracking ecosystem extent and pattern, chemical and physical characteristics, biological components, and goods and services derived from the natural world – for six key ecosystems: coasts and oceans, farmlands, forests, fresh waters, grasslands and shrublands, and urban and suburban landscapes.

Among the many conclusions of the 2008 report were that the acreage burned every year by wildfires was increasing; nonnative fishes had invaded nearly every watershed in the lower 48 states; and chemical contaminants were found in virtually all streams and most groundwater wells, often at levels above those set to protect human health or wildlife. On the plus side, ecosystems were increasing their storage of carbon, soil quality was improving, and crop yields had grown significantly.

The massive international UN Millennium Ecosystem Assessment remains the gold standard for synthesizing ecological conditions at a variety of scales. From 2001 through 2005, the project examined the full range of global ecosystems – from those relatively undisturbed, such as natural forests, to landscapes with mixed patterns of human use to ecosystems intensively managed and modified by humans, such as agricultural land and urban areas – and communicated its findings in terms of the consequences of ecosystem change for human well-being.

The resulting set of reports drew attention to the many kinds of services people rely on from ecosystems, specifically, supporting services, such as photosynthesis, soil formation, and waste absorption; regulating services, such as climate and flood control and maintenance of water quality; provisioning services, such as food, wood, and nature's pharmacopoeia; and cultural services from

Table 3 Biological attributes in two indexes of biological integrity for streams and rivers

Benthic invertebrates	*Fishes*
Total number of taxa	Number of native fish species
Number of mayfly taxa	Number of riffle-benthic insectivore species
Number of stonefly taxa	Number of water-column insectivore species
Number of caddisfly taxa	Number of pool-benthic insectivore species
Number of intolerant taxa	Number of intolerant species
Number of long-lived taxa	Relative abundance of omnivores
Number of clinger taxa	Relative abundance of insectivores
Relative abundance of tolerant taxa	Relative abundance of tolerant taxa
Relative abundance of predators	Relative abundance of top carnivores
Dominance	Relative abundance of diseased or deformed individuals

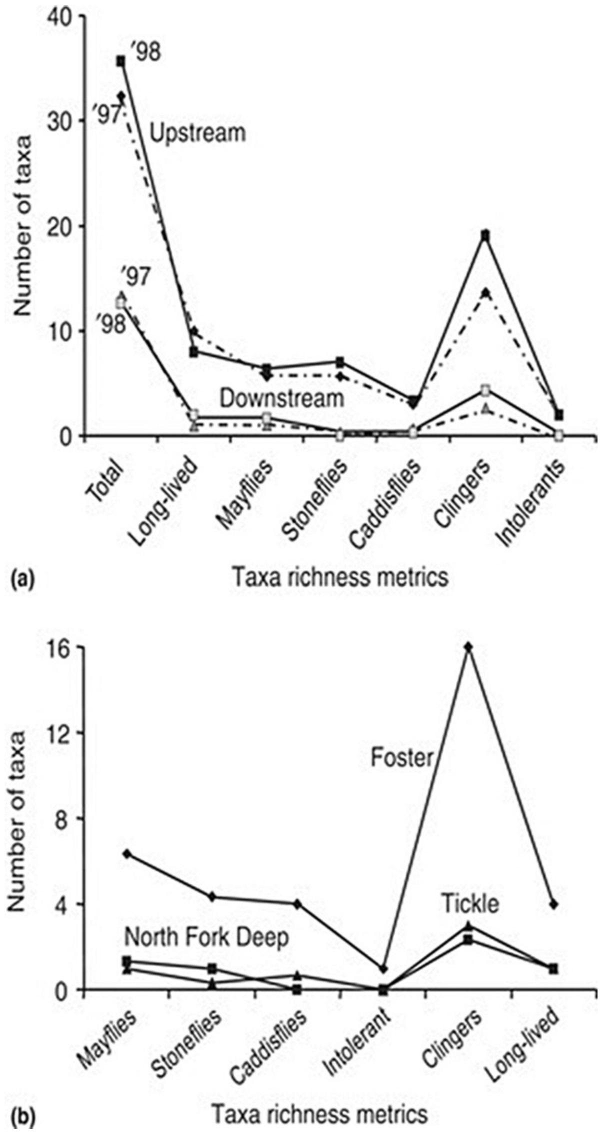

Fig. 2 (a) Biodiversity is higher at sites upstream of wastewater treatment outfalls than downstream. At Tickle Creek near Portland, Oregon (United States), taxa richness differed little between years but differed dramatically between sites upstream of a wastewater outfall and sites downstream. (b) Taxa richness also differed between two creeks with wastewater outfalls (Tickle and North Fork Deep) and one creek without an outfall (Foster). All three streams flowed through watersheds with similar land uses.

scientific to spiritual. In addition, the reports explicitly tied the status of diverse ecosystems and their service-providing capacity to human needs as varied as food and health, personal safety and security, and social cohesion. Even while recognizing that the human species is buffered against ecological changes by culture and technology, the reports highlighted our fundamental dependence on the flow of ecosystem services and our direct responsibility for the many faces of biotic impoverishment.

Among other findings, the assessment found that 60% of the services coming from ecosystems are being degraded, to the detriment of efforts to stem poverty, hunger, and disease among the poor everywhere. Declines are not limited to coral reefs and tropical forests, which have been on the public's radar for some time; they are pervasive in grasslands, deserts, mountains, and other landscapes as well. A leading cause of declines in renewable natural resources is government subsidies that offer incentives to overharvest. The degradation of ecosystem services could grow worse during the first half of the 21st century, blocking achievement of the United Nations' eight millennium development goals.

The core message embodied in ecological, especially biological, assessments is that preventing harmful environmental impacts goes beyond narrow protection of clean water or clear skies, even beyond protecting single desired species. Certain species may be valuable for commerce or sport, but these species do not exist in isolation. We cannot predict which organisms are vital for the survival of commercial species or species we want for other reasons. Failing to protect all organisms – from microbes and fungi to plants, invertebrates, and vertebrates – ignores the key contributions of these groups to healthy biotic communities. No matter

Table 4 Biological responses to different land uses

Region	*Land use*	*B-IBI*[a]
King County, Washington, United States	Rural	46
	Urban Seattle	12
Grand Teton Region, Wyoming, United States	Little or no human activity	48
	Light to moderate recreation	44
	Heavy recreation	32
	Urban Jackson Hole	21
Clackamas County, Oregon, United States[b]	Upstream of wastewater treatment plant	
	Tickle Creek up (1997, 1998)	40, 42
	Foster Creek	34
	Downstream of wastewater treatment plant	
	Tickle Creek down (1997, 1998)	14, 16
	North Fork Deep Creek	10

[a]Benthic index of biological integrity: the highest possible score is 50, the lowest is 10.
[b]See **Fig. 2** for graphs of selected B-IBI metrics at these sites.

how important a particular species is to people, it cannot persist outside the biological context that sustains it. Direct biological assessment objectively measures this context.

Recognizing and Managing Environmental Impacts

Every animal is alert to dangers in its environment. A microscopic protist gliding through water responds to light, temperature, and chemicals in its path, turning away at the first sign of something noxious. A bird looking for food must decide when to pursue prey and when not, because pursuit might expose it to predators. The bird might risk pursuit when hungry but not when it has young to protect. Animals that assess risks properly and adjust their behavior are more likely to survive; in nature, flawed risk assessment often means death or end of a genetic line.

People, too, are natural risk assessors. Each person chooses whether to smoke or drink, fly or go by train, drive a car or ride a motorcycle and at what speeds. Each decision is the result of a partially objective, partially subjective internal calculus that weighs benefits and risks against one another.

Risk is a combination of two factors: the numerical probability that an adverse event will occur and the consequences of the adverse event. People may not always have the right signals about these two factors, however, and may base their risk calculus on the wrong clues. City dwellers in the United States generally feel that it is safer to drive home on a Saturday night than to fly in an airplane, for example. Even though the numerical odds of an accident are much higher on the highway than in the air, people fear more the consequences of an airplane falling out of the sky.

Society also strives to reduce its collective exposure to risks. Governments routinely use military power to defend their sovereignty and, albeit more reluctantly, regulatory power to reduce workplace risks and risks associated with consumer products like cars. But people and their governments have been much less successful in defining and reducing a broad range of ecological risks, largely because they have denied that the threats are real.

Policies and plans generated by economists, technologists, engineers, and even ecologists typically assume that lost and damaged components of living systems are unimportant or can be repaired or replaced. Widespread ecological degradation has resulted directly from the failure of modern society to properly assess the ecological risks it faces. Like the fate of Old Kingdom Egypt or Easter Island, our civilization's future depends on our ability to recognize this deficiency and correct it.

Risk assessment as formally practiced by various government agencies began as a way to evaluate the effects of toxic substances on human health, usually the effects of single substances, such as pollutants or drugs, from single sources, such as a chemical plant. During the 1990s, the focus widened to encompass mixtures of substances and also ecological risks. For example, ecological risk assessment by the US Environmental Protection Agency (1998) started by asking five questions: Is there a problem? What is the nature of the problem? What are the exposure and ecological effects? (A hazard to which no one or nothing is exposed is not considered to pose any risk.) How can we summarize and explain the problem to affected parties, both at-risk populations and those whose activities would be curtailed? How can we manage the risks?

Even though these were good questions, ecological risk management has made no visible headway in stemming biotic impoverishment. Its central failing comes from an inability to correctly answer the second question, What is the nature of the problem? Our present political, social, and economic systems simply do not give us the right signals about what is at risk. None of society's most familiar indicators – whether GDP or number of threatened and endangered species – measure the consequences, or risks, of losing living systems.

If biotic impoverishment is the problem, then it only makes sense to direct environmental policy toward protecting the integrity of biotic systems. Integrity implies a wholeness or unimpaired condition. In present biological usage, integrity refers to the condition at sites with little or no influence from human activity; the organisms there are the products of natural evolutionary and biogeographic processes in the absence of people. Tying the concept of integrity to an evolutionary framework lays down a benchmark against which to evaluate sites that people have altered.

Directing policy toward protecting biological integrity – as called for in the United States' Clean Water Act, Canada's National Park Act, and the European Union's Water Framework Directive, among others – does not, however, mean that people must cease all activity that interferes with some "pristine" Earthly biota. The demands of feeding, clothing, and housing billions of people mean that few places on Earth will maintain a biota with evolutionary and biogeographic integrity. Rather, because people depend on living systems, it is in our interest to manage our activities so they do not compromise a place's capacity to support those activities in the future; that capacity can be called ecological health.

Ecological health describes the preferred state of sites heavily used for human purposes: cities, croplands, tree farms, water bodies stocked for fish, and the like. At these places, it is impractical to set a goal of integrity in an evolutionary sense, but we should avoid practices that damage these places or places elsewhere to the point that we can no longer receive the intended benefits indefinitely. For example, agricultural practices that leave behind saline soils, depress regional water tables, and erode fertile topsoil faster than it can be renewed destroy the land's biological capacity for agriculture. Moreover, they can degrade places downstream and downwind – locally, regionally, and across an ocean or continent. Such practices are unhealthy in both ecological and economic terms.

Biological integrity as a policy goal redirects our focus away from maximizing goods and services for the human economy and toward ways to manage our economy within the bounds set by the natural economy. It begins to turn our attention away from questions such as, How much stress can landscapes and ecosystems absorb? to ones such as, How can responsible human actions protect and restore ecosystems? In contrast to risk assessment, striving to protect biological integrity would lead us away from technological fixes for environmental problems and toward practices that prevent ecological degradation and encourage ecological restoration.

Leopold (1949, pp. 224–225), in *A Sand County Almanac*, was the first to invoke the concept of integrity in an ecological sense: "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise." Managing for biological integrity requires the kind of ethical commitment inherent in Leopold's words. We are called to restrain consumerism and limit population size, to embrace less-selfish attitudes toward land stewardship, and to understand that the biosphere matters. Instead of calling on human technical and spiritual wellsprings to manage resources, we have to call on them for managing human affairs.

We have to set goals and craft indicators, as the United Nations and others are doing. These goals and indicators must conform to the biophysical realities at work in the world and acknowledge humans' propensity to put narrow self-interest above all else. We have to find and use appropriate measurements for all the factors contributing to biotic impoverishment, be they climate change, overharvesting, agriculture, or environmental injustice. Measurement of environmental impact founded on the evolutionary idea of integrity means directly assessing biotic condition and comparing that condition with what might be expected in a place with little or no human influence. We can then make an informed choice: continue with activities that degrade biotic condition or create alternatives that do not harm living systems.

Modern institutions are capable of recognizing ecological threats and responding to them in time, as they did with the Montreal Protocol. A decade after the agreement's adoption, satellite measurements in the stratosphere indicated that ozone-depleting pollutants were in fact declining. Given this success, some policy experts have hoped the ozone treaty can also help slow global warming. Specifically, negotiators at the 2015 annual meeting of signatory parties agreed to develop an amendment to the Montreal Protocol. The amendment's goal is to phase out the production and use of industrial chemicals called hydrofluorocarbons, which have thousands of times the global warming potential of carbon dioxide. Even though the ozone treaty was not designed to fight climate change, policymakers say that it can and should be used to achieve broader environmental objectives.

In another hopeful move, the world's 195 nations signed in Paris in December 2015 the most ambitious climate accord to date. The agreement commits them to taking concrete measures to cut carbon emissions and pursue efforts to limit global temperature increase to 1.5°C above preindustrial levels. Developed countries are to bear the brunt of mobilizing the financing to put such measures in place. The accord is widely viewed as a landmark, although the commitments are largely voluntary, and the results remain to be seen.

Reuniting the Fragments

Early in the 20th century, two sciences of "home maintenance" began to flourish: the young science of ecology (from the Greek *oikos*, meaning home) and a maturing neoclassical economics (also from *oikos*). Ecology arose to document and understand the interactions between organisms and their living and nonliving surroundings – in essence, how organisms make a living in the natural economy. In fact, Ernst Haeckel, who coined the term in the 1860s, defined ecology in an 1870 article as the body of knowledge concerning the economy of nature. Neoclassical economics, in contrast, reinforced humans' self-appointed dominion over nature's wealth. It brought unparalleled gains in societal welfare in some places, but it also divorced the human economy from the natural one on which it stands (see **Fig. 1**).

In his *Short History of Progress*, Wright (2004, p. 8) recounts tales of "progress traps" that humanity has fallen into; each time history repeats itself, he reminds us, the price goes up. By now it is clear to economists and ecologists alike that human progress has reached scales unprecedented in the history of life. We have altered Earth's physical and chemical environments, changed the planet's water and nutrient cycles, and perturbed its climate. We have unleashed the greatest mass extinction in 65 My and distorted the structure and function of nonhuman and human communities worldwide. In trying to make our own living, we have jeopardized Earth's capacity to sustain other species and our own species as well. We are losing life on Earth – the *bio* in biosphere.

Confronted with these unprecedented losses, we need to understand – not deny – the ecological consequences of what we do. We urgently need a new craft of home maintenance, one that sees the human species' role as ecosystem engineer for what it has become – *the* global agent of change. Despite uncertainty, we need to act to prevent environmental harm and to reconnect human with natural economies. By using indicators that measure what matters for sustaining living systems, we can make nature visible again and shed new light on the value of the ancient heritage we share with the larger biosphere. We can reunite the fragments of our worldview and re-create ethical, social, and ecological bonds that were put aside two centuries ago in the name of progress. And we can reengineer our own social, political, and economic institutions instead of ecosystems. This we must do – now – before we impoverish the biosphere and risk our own survival for all time.

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